Hydrogen Behavior in Containment

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Outline

- Phenomenon and Definition
- Limited and Severe Core Damage Accidents
- Hydrogen Source Terms
- R&D Programs on Hydrogen Behavior
  - Hydrogen Test Facilities at AECL
  - Hydrogen Distribution (as attachment)
  - Hydrogen Combustion (as attachment)
  - Hydrogen Mitigation (as attachment)
  - Analysis Tools
- Summary

Hydrogen Behavior During Limited and Severe Core Damage Accidents

- During the limited or severe core damages accidents in CANDU reactors, hydrogen can be formed by zirconium-steam reactions, radiolysis and corrosion of metal. Hydrogen may migrate to the containment building creating a combustible atmosphere. Thermal and mechanical loads to containment structures resulting from ignition of the hydrogen are safety concerns.

Types of Accidents

- **Limited Core Damage Accidents**

  (e.g., LOCA + LOECC)
  - Cause fuel damage in a single or multiple channels
  - Reactor core is not severely damaged because moderator provides a back-up to remove decay heat
  - Hydrogen is formed by Zirconium-steam reactions and eventually accumulates in containment
- **Severe Core Damage Accidents**

  (e.g., LOCA + LOECC + unavailability of moderator heat sink)
  - Cause reactor core damage
  - While there can be loss of channel geometry, water in the calandria vessel and shield tank prevents core expulsion
  - Larger hydrogen source term
  - An extremely improbable event in CANDU reactor

Examples of Events

- **Limited Core Damage Accidents**
  - Small LOCA + LOECC
  - End Fitting Failure + LOECC
  - Large LOCA + LOECC
  - Pressure Tube / Calandria Tube Failure + LOECC
  - Steam Generator Tube Rupture + LOECC
  - Stagnation Feeder Break
  - Severe Channel Flow Blockage
- **Severe Core Damage Accidents**
  - LOCA + LOECC + unavailability of moderator heat sink

Hydrogen Source Term

- **Hydrogen release in containment**
  - Short term (< 1 day)
    - Zirconium-steam reactions
    - Hydrogen degassing
  - Long term (> 1 day)
    - Radiolysis
    - Corrosion of metal

Typical Hydrogen Source Terms for LOCA + LOECC Accidents

(Typical hydrogen source term for CANDU 6)

- Zirconium-steam reactions
  - 65 kg of hydrogen (1500 m^3)
- Hydrogen degassing
  - 0.3 kg of hydrogen (3.5 m^3)
- Radiolysis
  - 30 kg/day from moderator water
  - 7 kg/day from sump water
  - 0.7 kg/day from moisture
  - Total 37.7 kg /day (890 m^3/day)
- Corrosion of Aluminum
  - Maximum 40 kg after 5 days

Hydrogen Mitigation Strategies

- Gas Mixing - (distribution of hydrogen)
  - Natural convection
  - Local air coolers
- Passive Autocatalytic Recombiner, PAR - (removal of hydrogen)

Hydrogen Mitigation

- Containment design promotes hydrogen mixing and distribution by natural convection
- Local air coolers prevent local stratification of hydrogen
- Hydrogen catalytic recombiners remove hydrogen
  - Self start at ~2% H_2
  - Passive device
  - Effective for long term hydrogen management

Impact of Hydrogen Burns in Containment

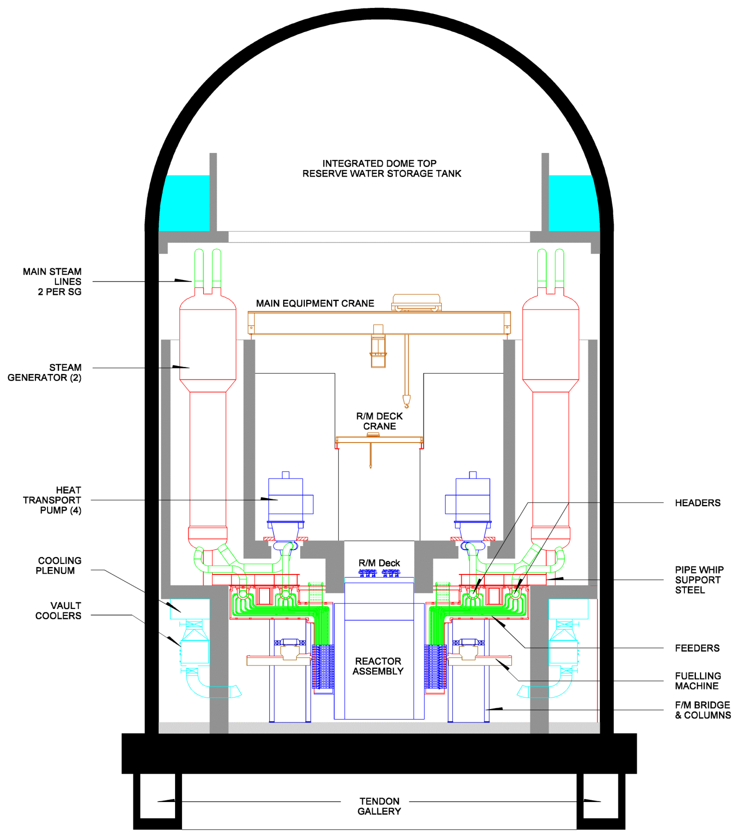
- **Standing flames**
  - H_2 diffusion flame at the break created by auto-ignition or a flash back
  - Thermal load
- **Hydrogen explosion (deflagration)**
  - H_2 ignited accidentally by hot surfaces or electrical sparks
  - Static and dynamic pressures
- **Detonation**
  - Via a Deflagration to Detonation Transition
  - Blast waves

Understanding Hydrogen Behavior

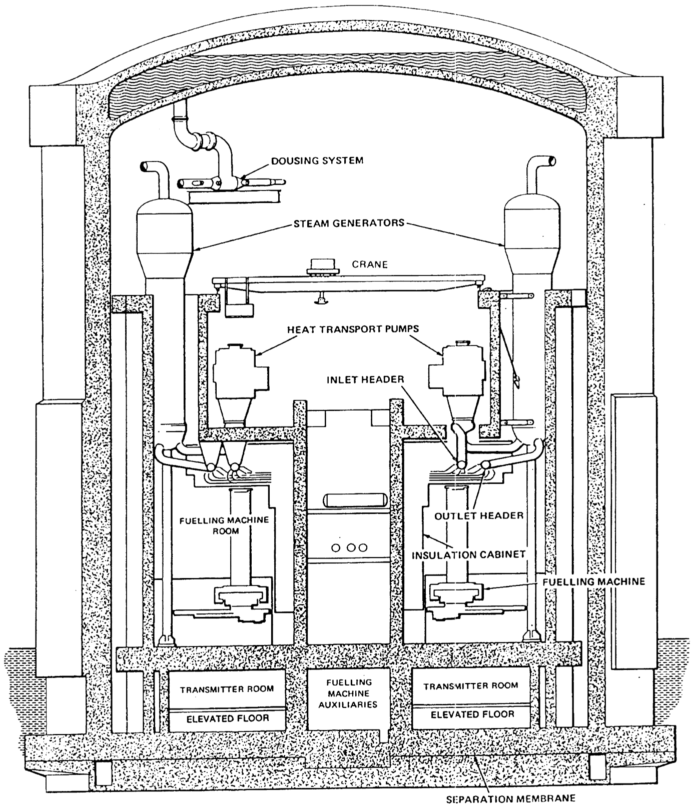
- Based on an extensive research program in the past 30 years in studying hydrogen behavior for existing CANDU reactors, an understanding of the key phenomena has been achieved
- Computer codes have also been developed to analyze hydrogen behavior for various accident scenarios
- These tools can be used to analyze postulated accidents in ACR

CANDU Containment

ACR



CANDU 6



R&D Program on Hydrogen Behavior at AECL

- AECL has a comprehensive R&D program to acquire understanding of key phenomena and to develop tools for accident analysis since early 1970s. Areas of research include:
  - Hydrogen Distribution
  - Hydrogen Combustion
  - Hydrogen Mitigation
  - Containment Response

Goals of R&D Programs

- Acquire fundamental understanding of key combustion phenomena relevant to postulated CANDU reactor accident scenarios
- Develop computer models for predicting gas distribution and combustion pressure

Hydrogen Programs at AECL

- **Recent research programs include:**
  - Gas distribution under accident conditions
  - Mechanisms and dynamics of standing flames
  - Mechanisms and dynamics of vented combustion
  - Flame acceleration and transition to detonation
  - Dynamics of flame jet ignition
  - Burn model development and validation

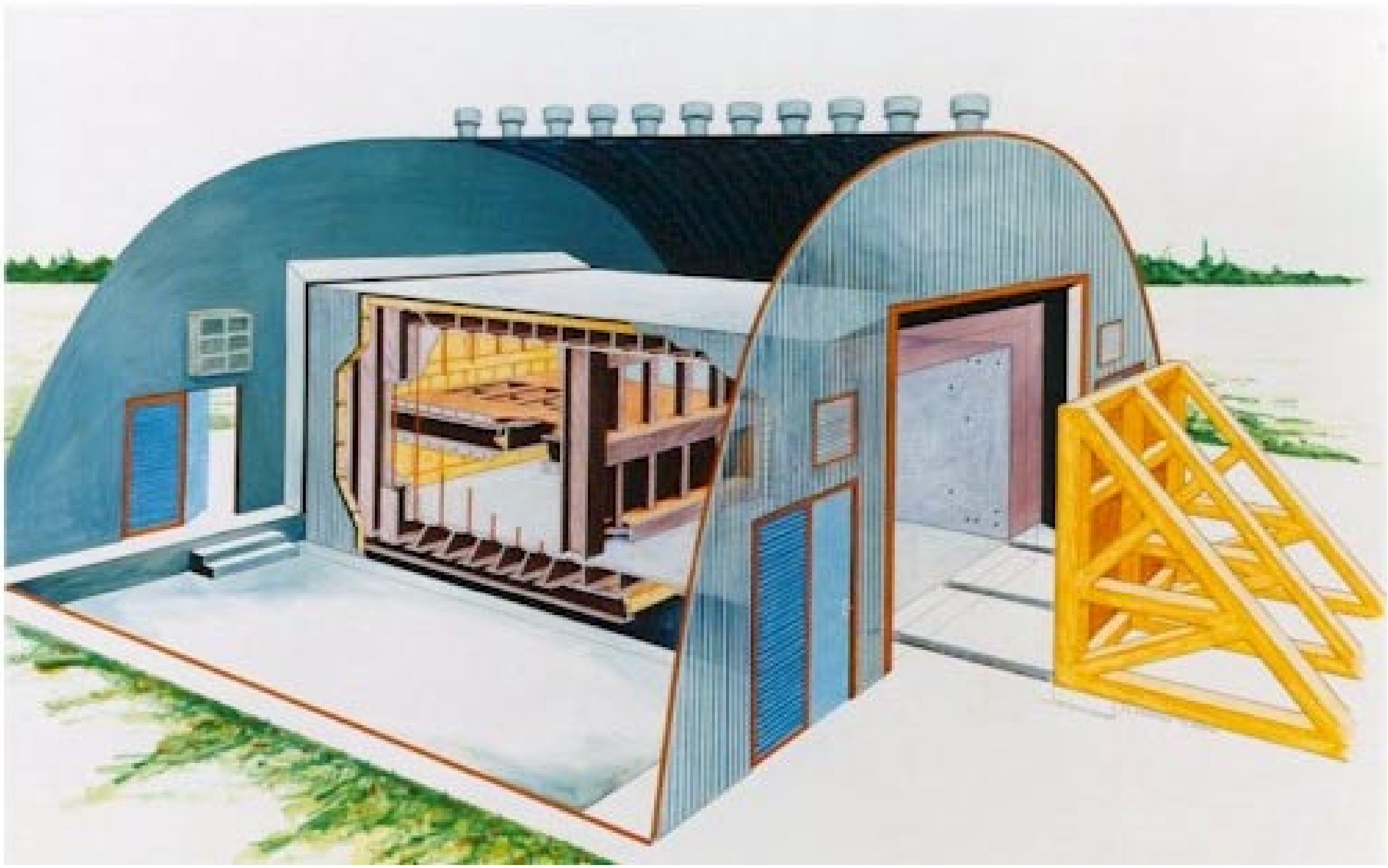
Research Facilities for Hydrogen

- Large Scale Vented Combustion Test Facility
- Containment Test Facility
- Diffusion Flame Facility
- Large Scale Gas Mixing Facility

Large Scale Vented Combustion Test Facility (LSVCTF)

The Large-Scale Vented Combustion Test Facility (LSVCTF) is a 10-m long, 4-m wide, 3-m high rectangular enclosure with an internal volume of 120 m^3. The test chamber, including the end walls, is electrically trace-heated and heavily insulated to maintain temperatures in excess of 100^{o}C for extended periods of time. The combustion chamber can be subdivided into 2 or 3 compartments. Variable sizes of vent openings are available between compartments and to the outside.

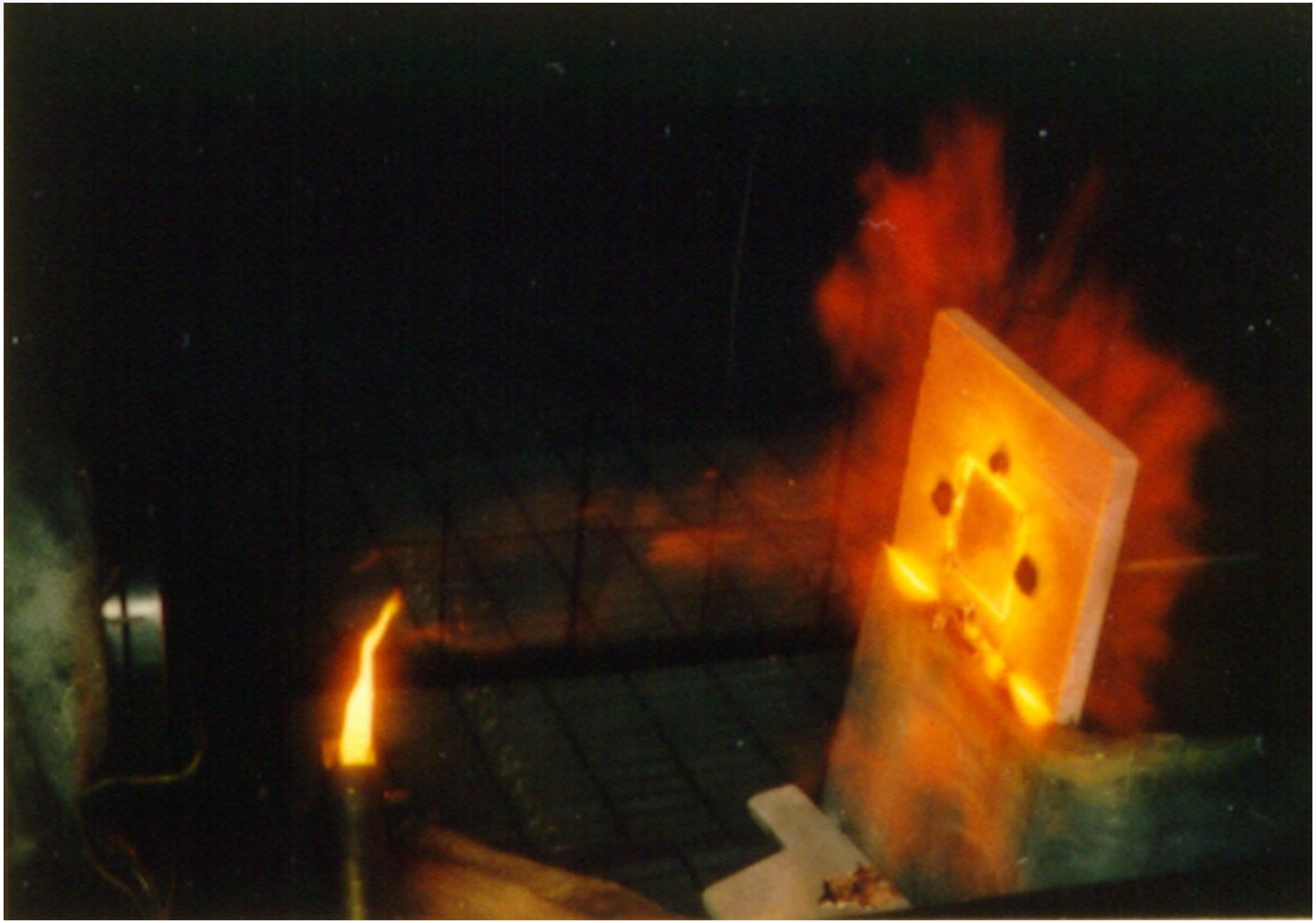
Large Scale Vented Combustion Test Facility



Diffusion Flame Facility (DFF)

The Diffusion Flame Facility (DFF) consists of a burner with associated gas supply lines and instrumentation housed within a modified grain silo (5 m diameter and 8 m height), which is insulated to retain heat for experiments that involve an air / steam environment. Tests with H_2 / steam jet flames (up to 15 cm in diameter) in air / steam atmosphere (up to 30% steam by volume) can be performed in this facility.

Hydrogen Diffusion Flame



Containment Test Facility (CTF)

The Containment Test Facility (CTF) consists of a 6-m^3 sphere and a 10-m^3 cylinder, both rated for pressures up to 10 MPa and trace-heated for operation at temperatures up to 150^{o}C. The large vessels may be inter-connected by 30 cm and 50 cm diameter ducts. The CTF is designed to investigate the fundamentals of combustion phenomena. These include flammability limits, ignition, turbulent combustion, flame acceleration, detonation, detonation transition.

Containment Test Facility

A 28cm-diameter and 9m-long combustion pipe with a design pressure of 10MPa. Obstacles can be mounted inside this pipe to induce flame acceleration. This apparatus has been used to determine the run-up distances for supersonic flames and DDT.

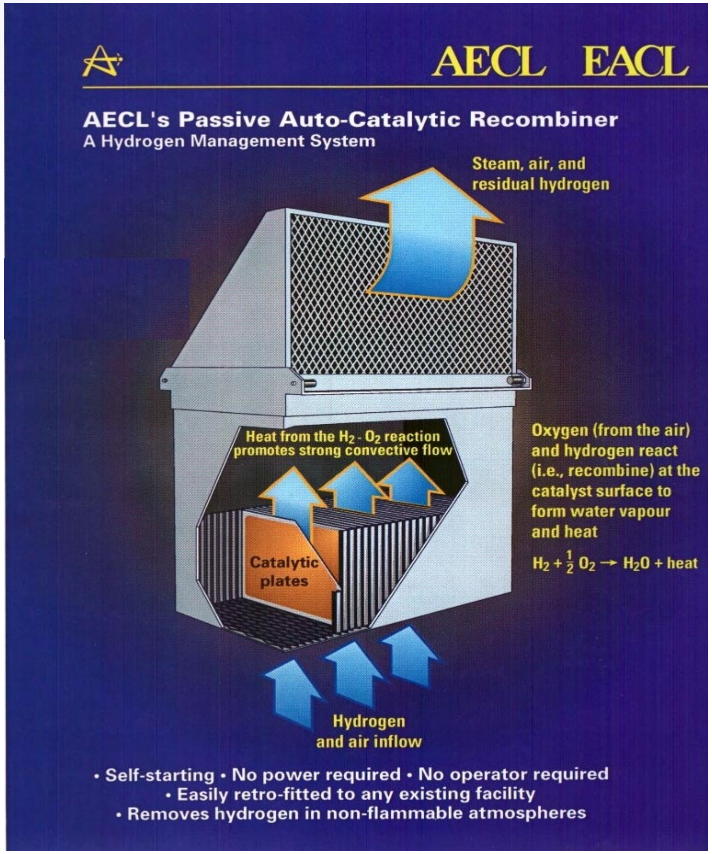
Large Scale Gas Mixing Facility (LSGMF) at Whiteshell Laboratories

Large-Scale Gas Mixing Facility

AECL's Large-Scale Gas Mixing Facility (LSGMF) is a 10.3 m by 11.0 m by 8.2 m concrete enclosure with an internal volume of approximately 1000 m^3. Helium and steam can be injected into the enclosure at various locations to simulate a break in the primary cooling system inside a reactor containment building following an accident. Internal partitions can also be added to the facility to simulate sub-compartments inside a reactor building.

A new facility is being constructed at AECL's Chalk River Laboratories (CRL)

AECL Passive Autocatalytic Recombiner



- recombine hydrogen with oxygen in a controlled fashion
- based on AECL's wet-proofed catalyst technology
- have been qualified with tests in the large-scale vented combustion facility

R&D Programs on Hydrogen

- **Details of selected R&D programs are included as attachments to this presentation**
  - **Hydrogen distribution**
  - **Hydrogen diffusion flames**
  - **Vented combustion in a complex geometry**
  - **Flame jet ignition**
  - **AECL PAR**

- **Analysis tools and analysis strategy are discussed in this presentation**

Analysis Tools

GOTHIC (mechanistic approach)

- GOTHIC (Generation of Thermal-Hydraulic Information for Containment) is a general purpose computer code for thermal hydraulic and combustion calculations (in 3-dimensional or hybrid mode)
- GOTHIC, with addition of CANDU-specific models for hydrogen behavior, is used to model containment thermal hydraulics and hydrogen transport
- It also calculates the combustion pressure in the event of an ignition
- It cannot predict supersonic flames and DDT

DDTINDEX (upper-bound approach)

- Calculate a set of parameters for assessing the possibility of flame acceleration to supersonic velocities and subsequently trigger a transition to detonation

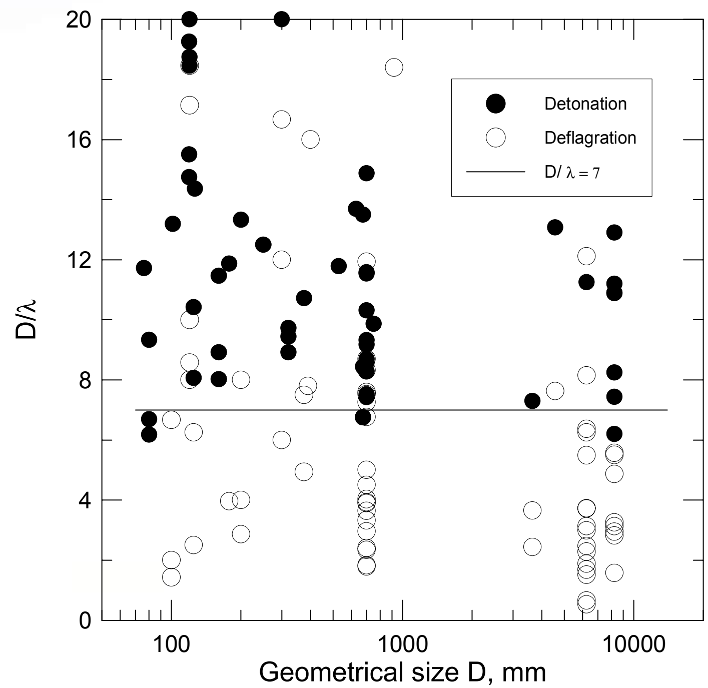
Potential Hazards for Supersonic Flames and Detonations

- The hydrogen cloud can be ignited accidentally creating a gas explosion inside the containment building
- An expanding flame is intrinsically unstable
- In the presence of obstacles, a flame can potentially accelerate to supersonic velocities and subsequently lead to Deflagration to Detonation Transition (DDT)
- Impact of pressure waves associated with supersonic flames (>500 kPa) and detonations (>1500 kPa) need to be understood

Assessing Potential for Supersonic Flames and DDT

- Criteria (necessary conditions in the form of a set of non-dimensional parameters) for flame acceleration to supersonic velocities and DDT have been experimentally determined
- If these criteria are not met, supersonic flames and detonations can be ruled out
- DDTINDEX calculates these parameters based on gas distribution information predicted by GOTHIC

Experimental Data for DDT



Summary of DDT Conditions in D/λ, where *D* is the Characteristic Dimension of a Room and λ is the detonation cell size

Source: OECD Nuclear Energy Agency State-of-the-Art Report on Flame Acceleration and DDT in Nuclear Safety (AECL is one of the contributor to this report)

Criteria for DDT (the λ criteria)

Transition to detonation requires L $> 7\lambda$,

where L is the cloud size

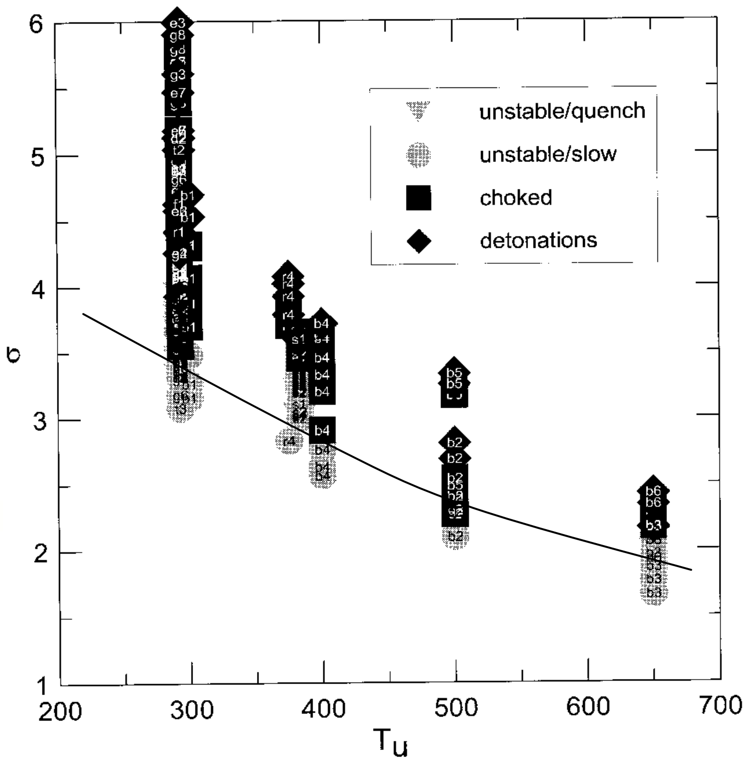
λ is the detonation cell width

DDT Index, ϕ_{DDT}=L/L*

DDT is not possible for $\phi_{DDT} < 1$

where L*= 7λ

Experimental Data for Flame Acceleration



Summary of flame acceleration conditions in σ, where σ is the expansion ratio

Source: OECD NEA State-of-the-Art Report on Flame Acceleration and DDT in Nuclear Safety

Criteria for Flame Acceleration to Supersonic Velocities (the σ criteria)

Flame Acceleration Index $\delta = \sigma/\sigma^*$

where σ is the expansion ratio (ρ_u/ρ_b)

Flame acceleration to supersonic velocities is impossible if $\delta<1$

$\sigma^* = 3.75$ for $X_{H2} =$ or $>2X_{O2}$, X is the gas mole fraction

$\sigma^* = 3.75 - 0.0115(T-25) + 0.00002(T-25)^2$ for $X_{H2} < 2X_{O2}$

where T is average temperature of the gas cloud in ^oC

DDT Potential
(a second criterion for DDT)

Since DDT cannot occur if the cloud size is less than the minimum run-up distance for DDT, a "DDT Potential" can also be defined as a second criterion for DDT.

DDT Potential, $\gamma_{DDT} = L/L_{DDT}$,

where L is the nominal diameter of the combustible gas cloud and L_{DDT} is the minimum run-up distance for DDT.

DDT is not possible for $\gamma_{DDT} < 1$.

Flame Acceleration (FA) Potential
(a second criterion for SF)

Since a flame requires physical distance (run-up distance) to accelerate to supersonic velocities, a "FA Potential" can also be defined as a second criterion.

The FA Potential, $\phi_{FA} = L/L_{SF}$,

where L is the nominal cloud size and L_{SF} is the run-up distance for a supersonic flame.

Flame acceleration to supersonic velocity is not possible for $\phi_{FA} < 1$.

DDTINDEX

- DDTINDEX calculates DDT Index, DDT Potential, FA Index and FA Potential for a non-uniform combustible gas cloud (predicted by GOTHIC)
- If all these parameters are less than 1, both supersonic flame and DDT can be ruled out
- The use of DDT Index and FA Index has been recognized internationally (OECD NEA State-of-the-Art Report) as a sound methodology for assessing the impact of hydrogen inside containment

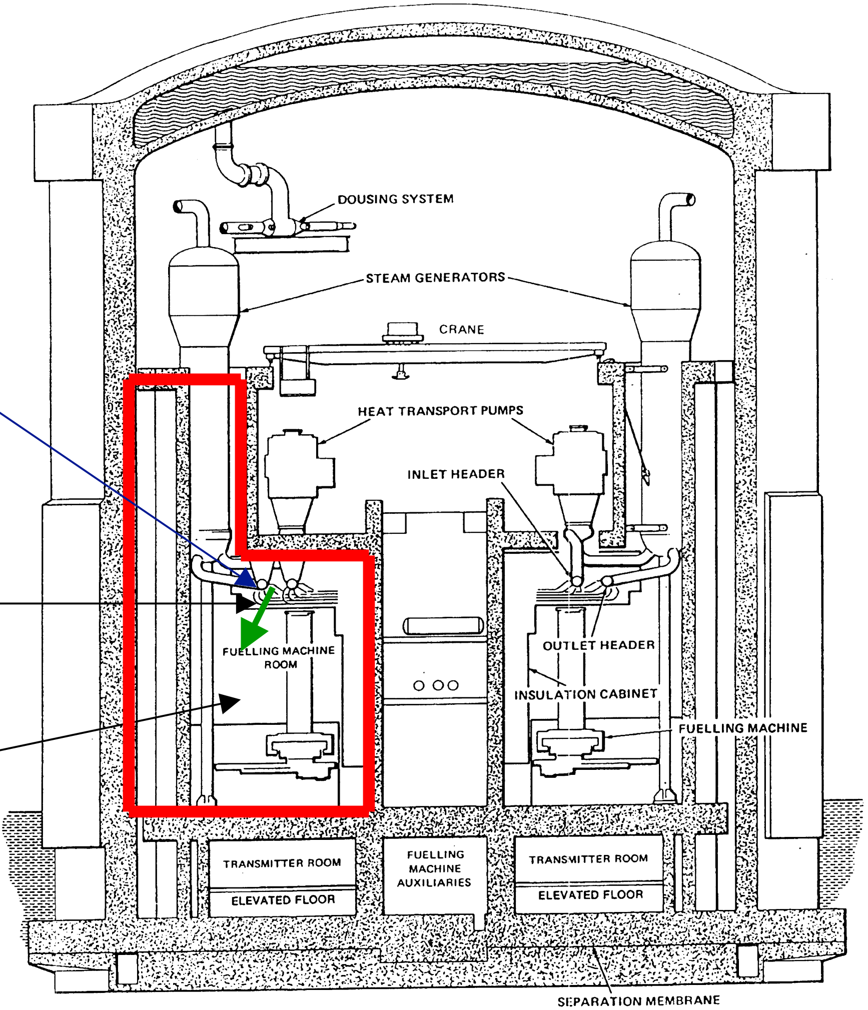
GOTHIC Simulation

Accident Scenario (hypothetical):

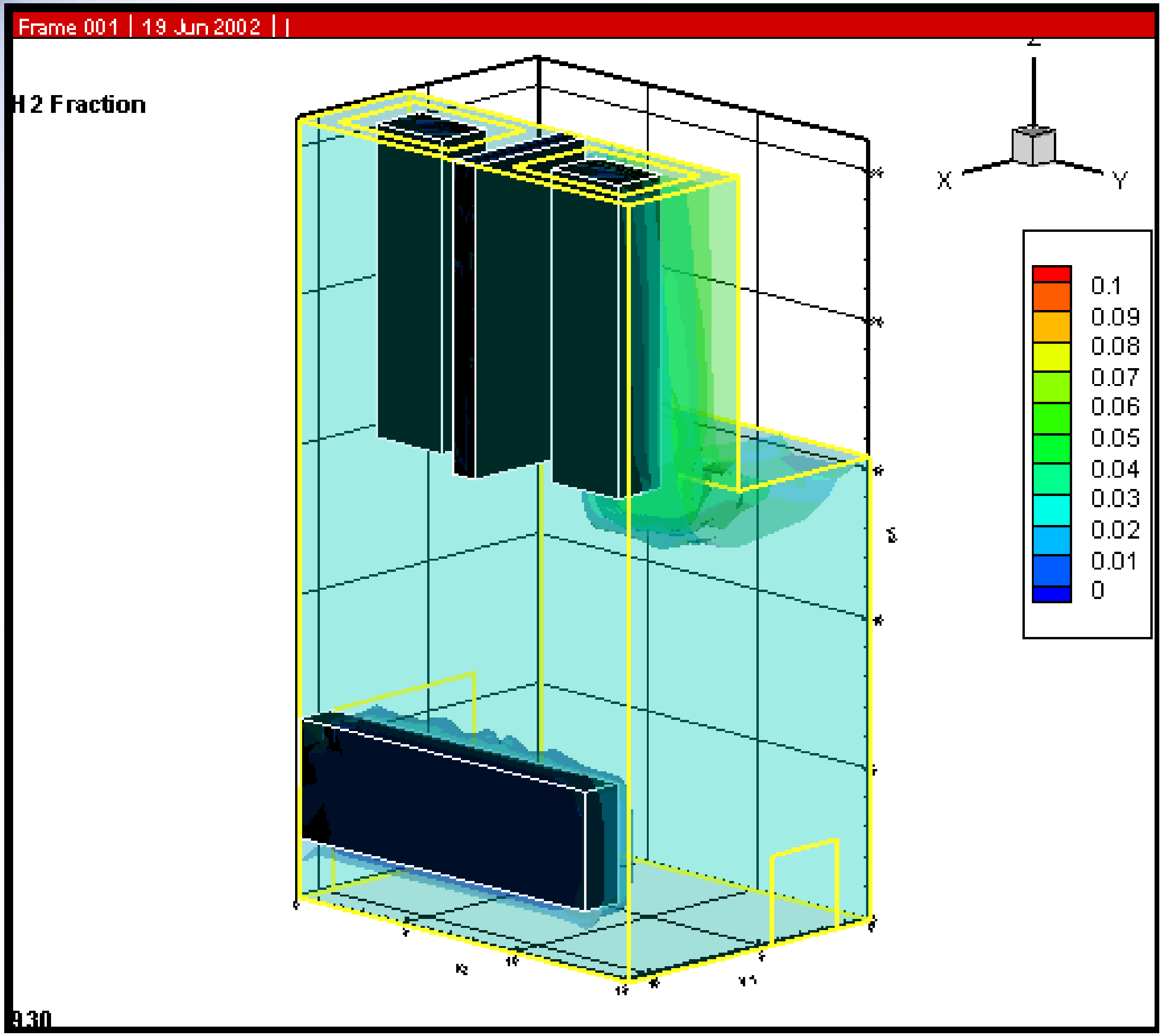
100% Header break in fueling machine vault

Header

Fuelling machine vault



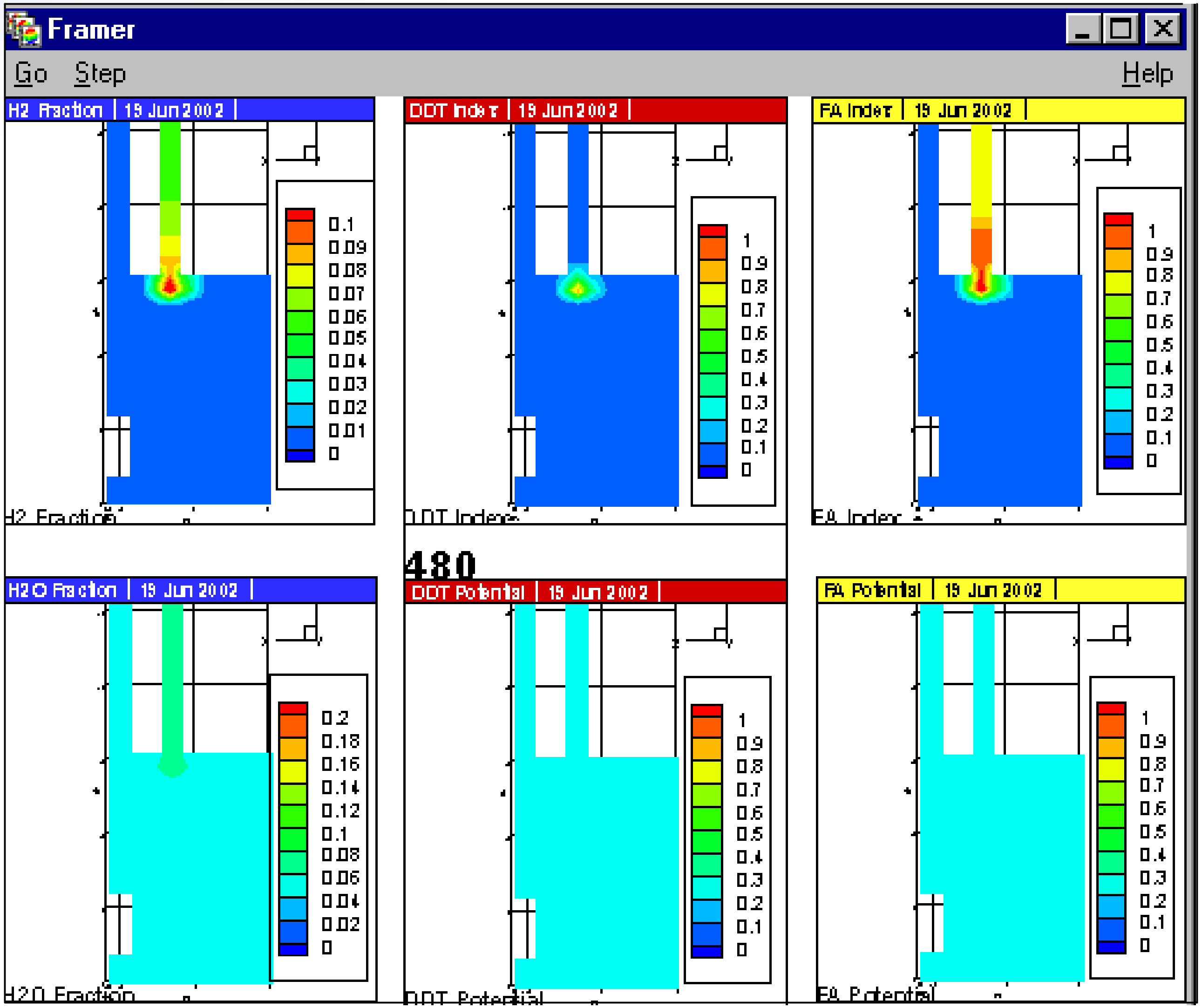
GOTHIC Simulation



- Hydrogen distribution in containment during a large LOCA (header break)

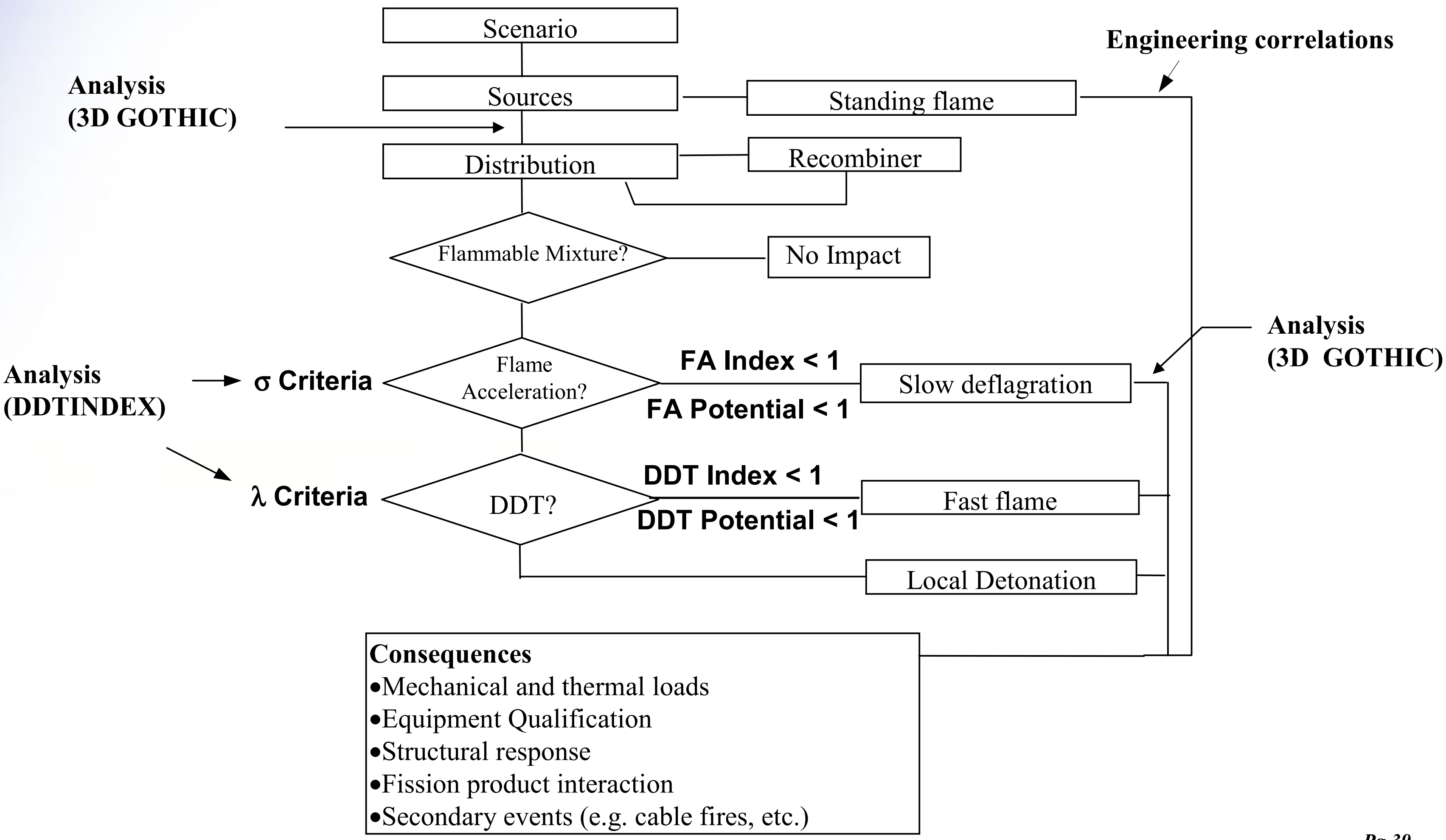
Animations

DDTINDEX Outputs



Animation

Strategy for Evaluating Hydrogen Hazards



Summary

- AECL has a mature and widely-recognized hydrogen program
- The dynamics and mechanisms associated with hydrogen combustion behavior in CANDU containment have been understood
- Models to capture the key phenomena have been developed and validated
- AECL has developed an accepted mitigation device (PAR) for CANDU and other reactor designs
- Knowledge base acquired in the past can be used to analyze reactor accidents relevant to ACR

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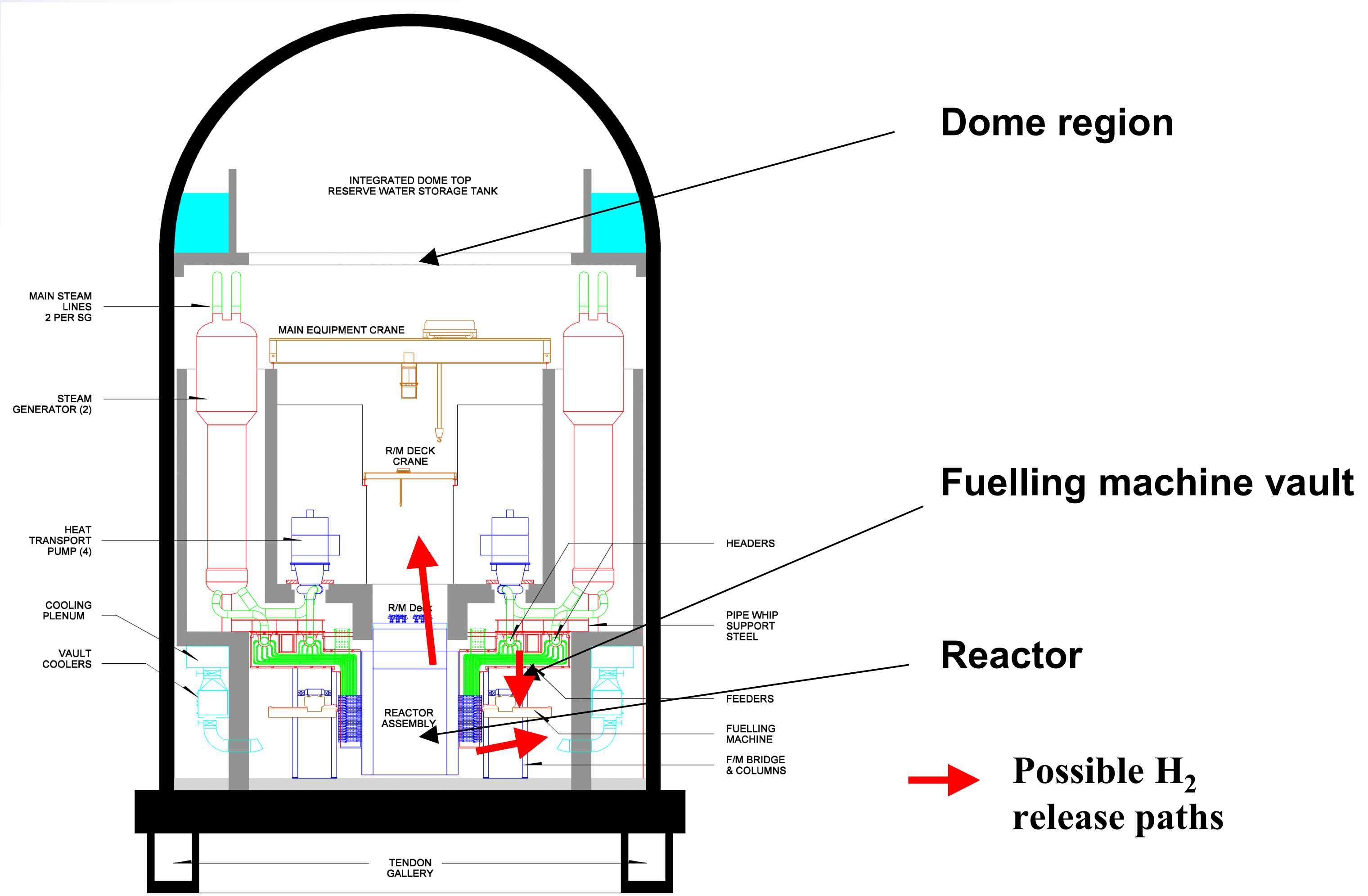
Research Activities on Hydrogen Behavior at AECL

Hydrogen Distribution

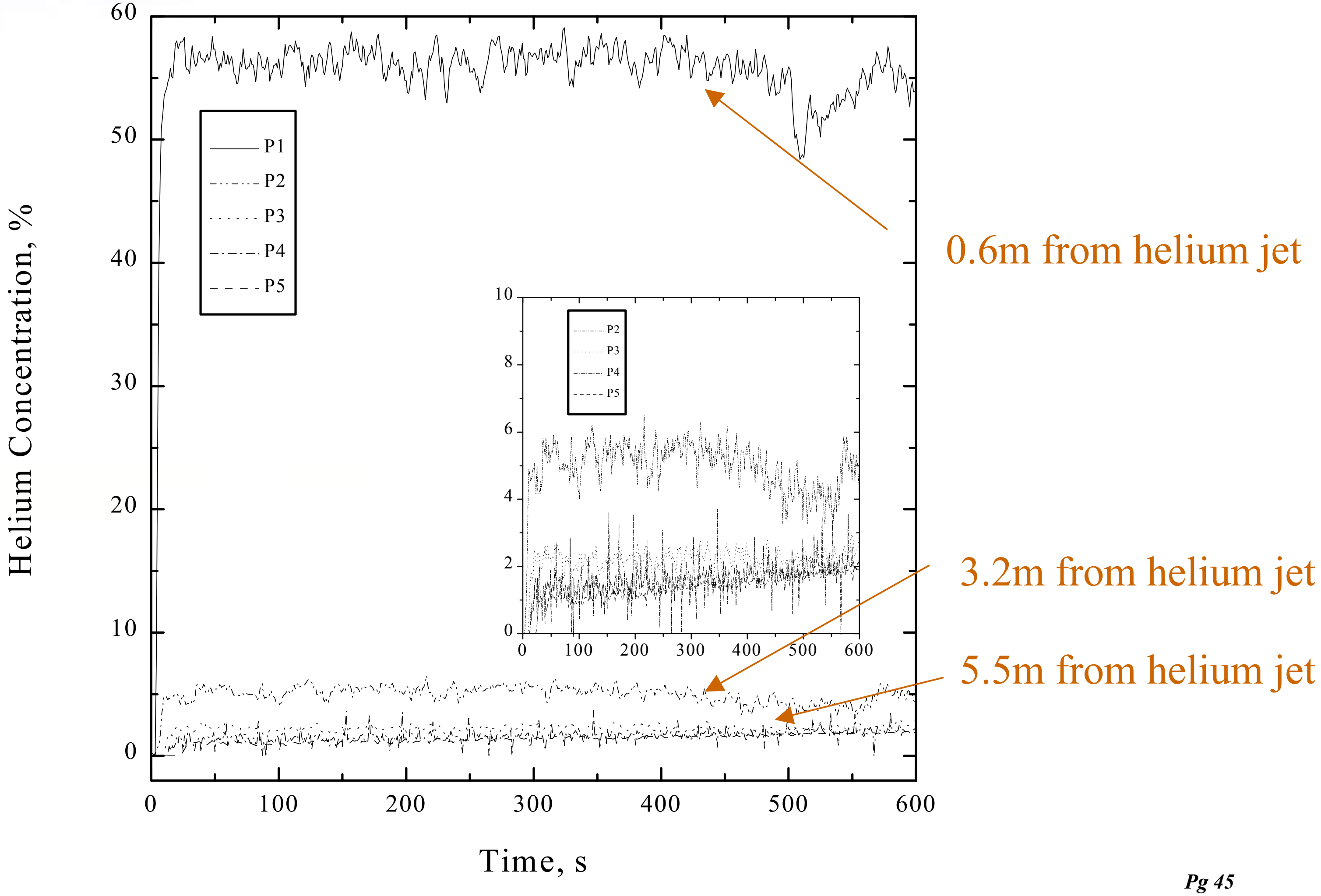
- Buoyancy driven mixing
- Gas mixing in a partitioned enclosure
- Containment code for gas distribution analysis (GOTHIC)

CANDU Containment




Large Scale Gas Mixing Facility (WL) - Interior

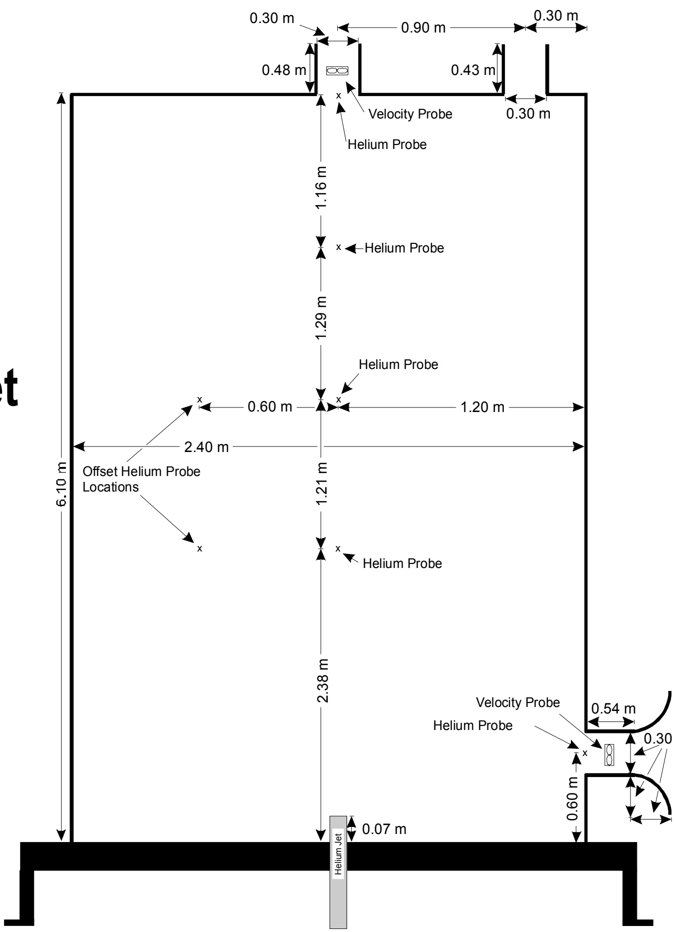
Buoyancy Driven Gas Mixing



Buoyancy Induced Convection in Partitioned Volumes

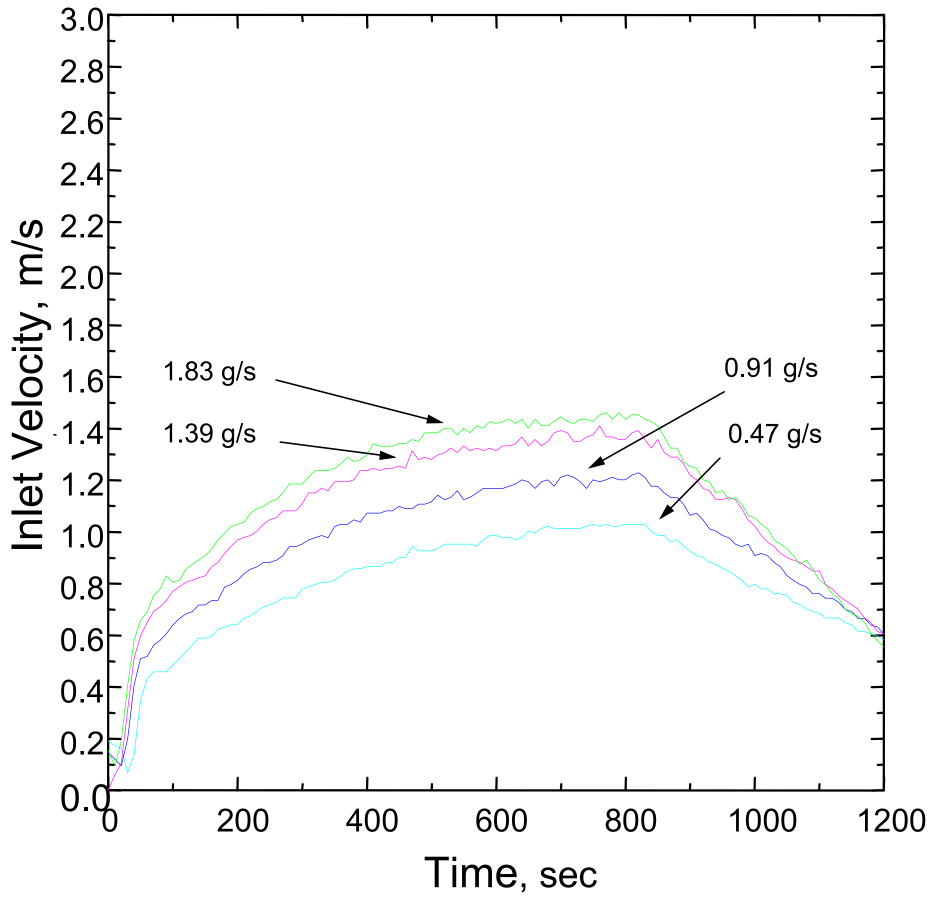
Experimental facility

- a 2.44 m x 2.44 m x 6.10 m enclosure
- Helium injection at bottom
- Helium concentration measurement
- Velocity measurement at inlet and outlet

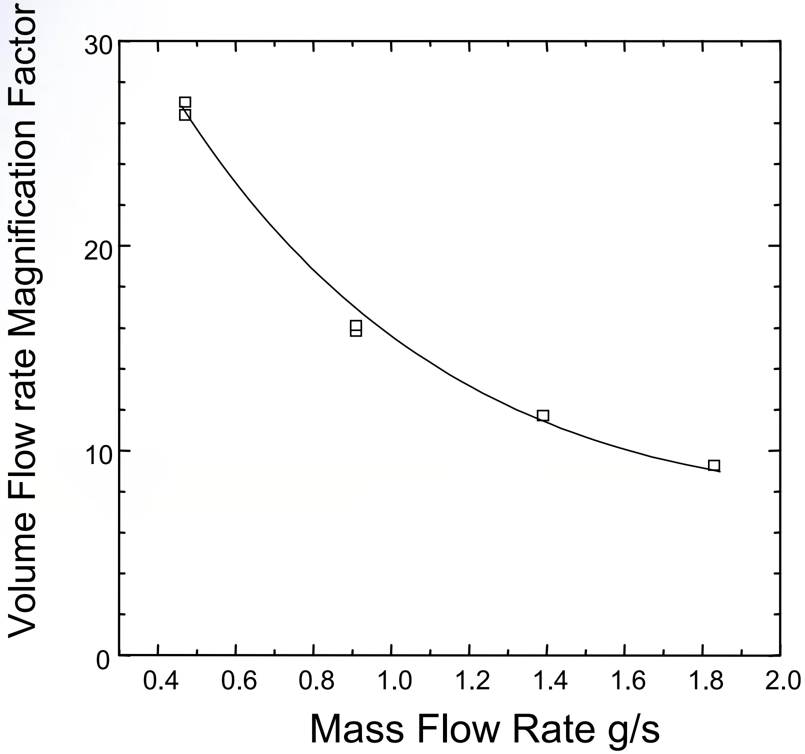


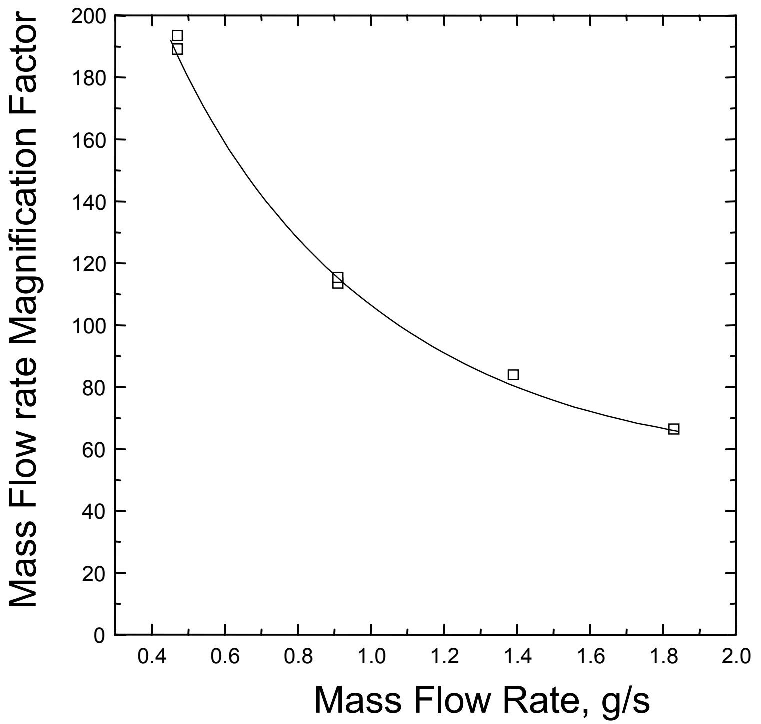
Buoyancy Induced Convection in Partitioned Volumes (cont.)

Inlet Velocity



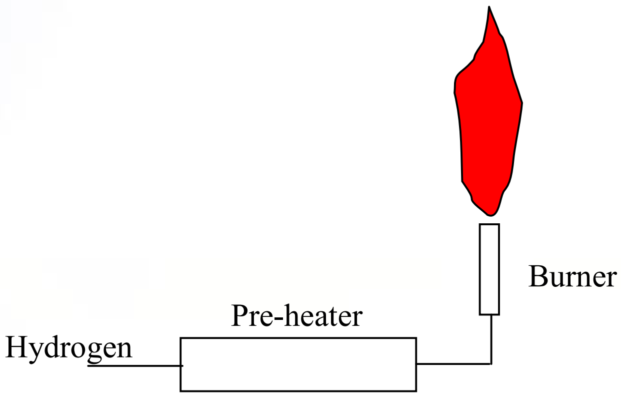
Buoyancy Induced Convection in Partitioned Volumes (cont.)

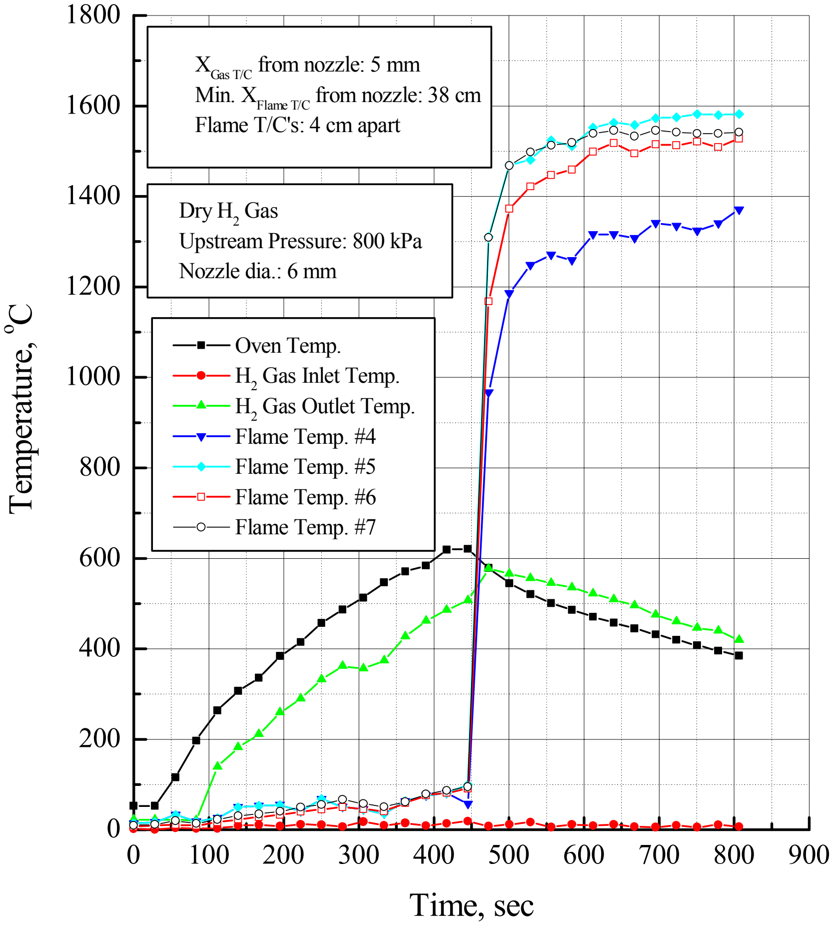




Hydrogen Diffusion Flame Facility

Hydrogen Diffusion Flame

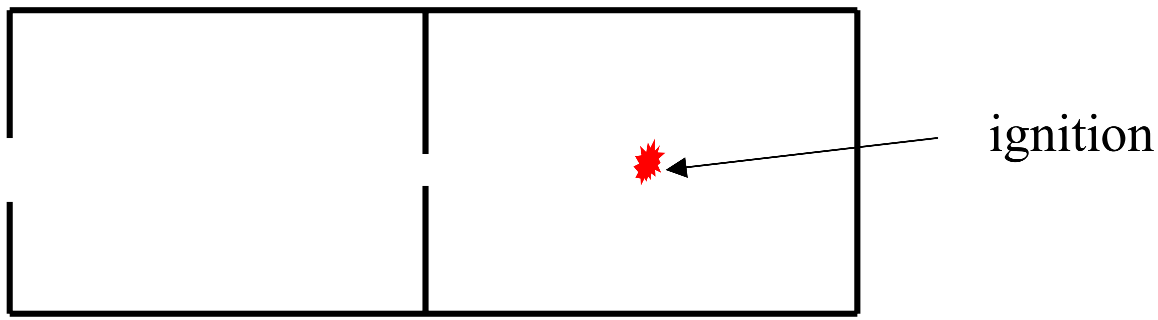




Flame Temperature of a Dry Hydrogen Jet Preheated to 500C

Large Scale Vented Combustion Test Facility

LSVCTF: Combustion in Interconnected Chambers



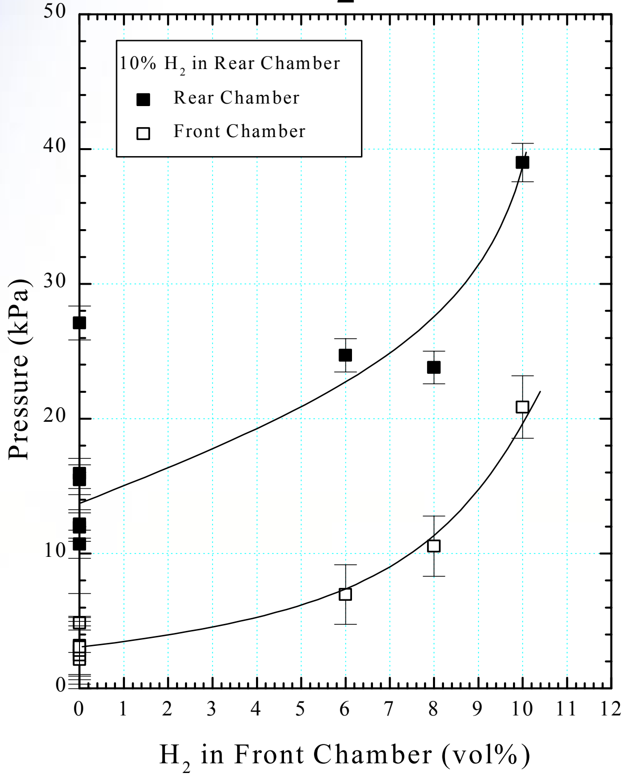
Inter-connected chambers exist in containment

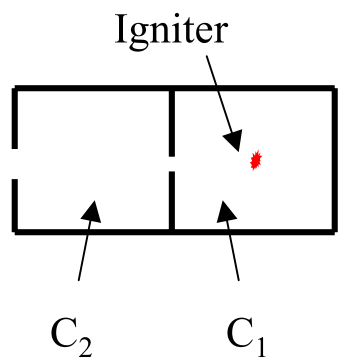
Specific Tests Series

- Variation in H_2% Between Chambers
- Variation of Vent Area
- Variation of Vent Location
- Variation of ignition location

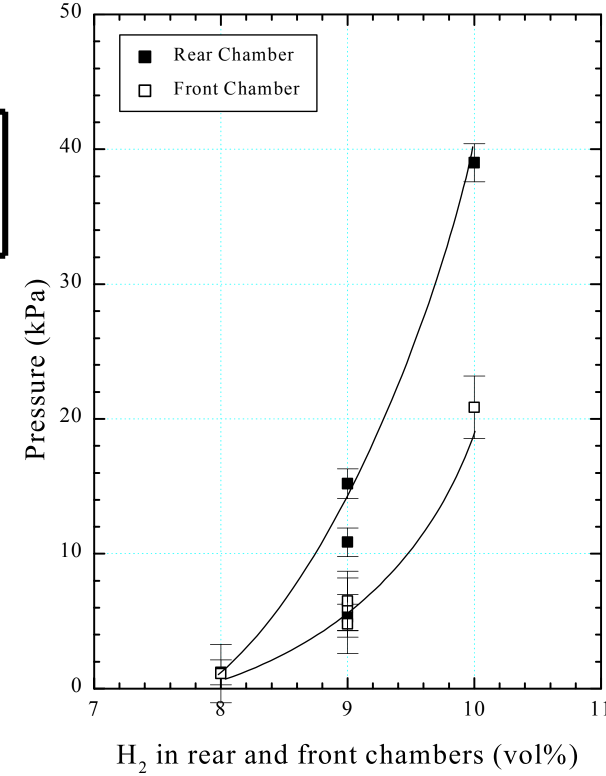
Combustion Pressure

Unequal H_2% ($C_1 > C_2$)

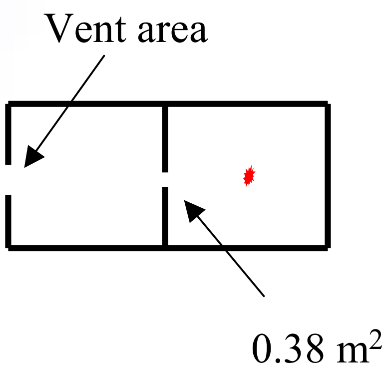


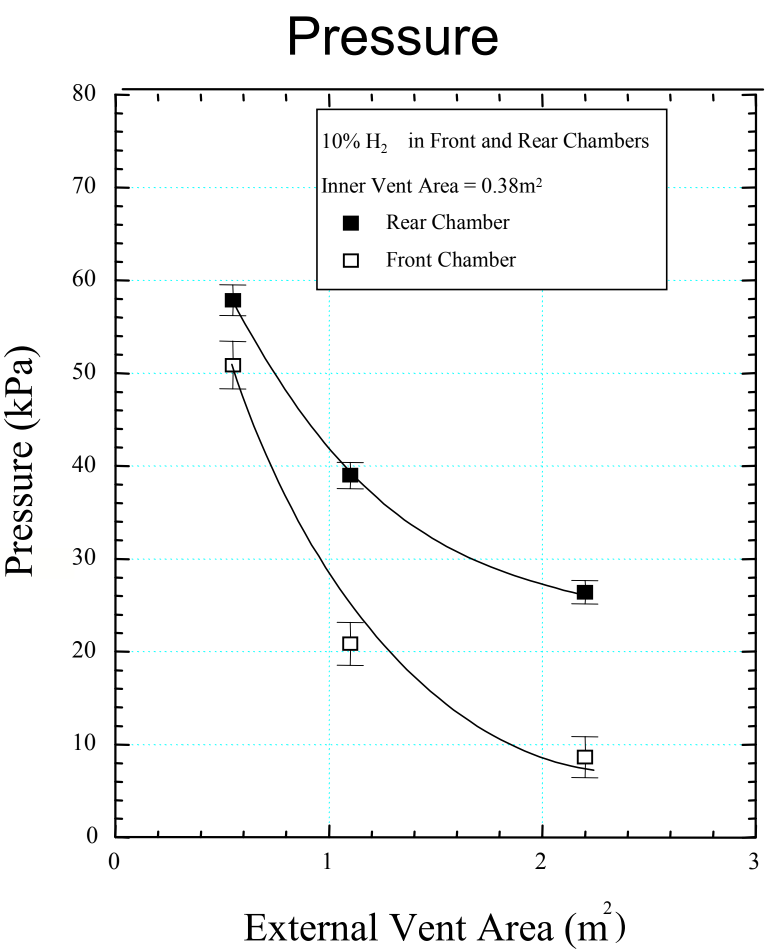


Equal H_2% ($C_1 = C_2$)



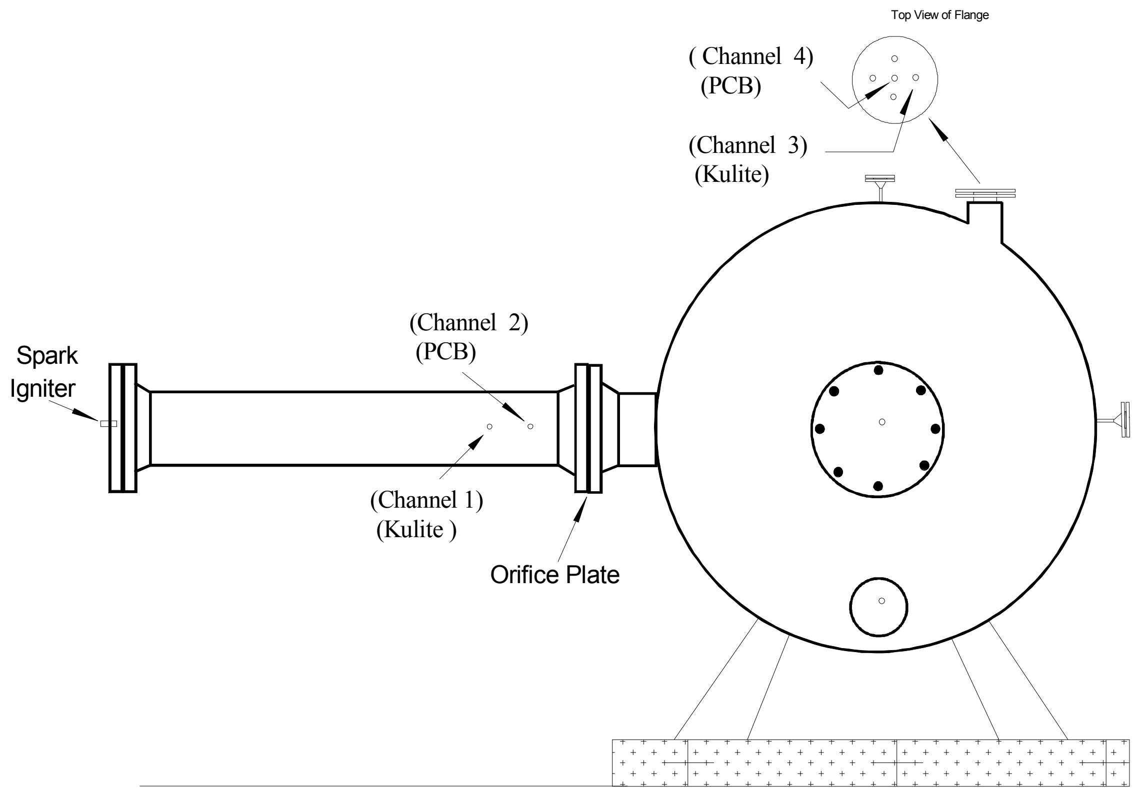
Variation of Vent Area



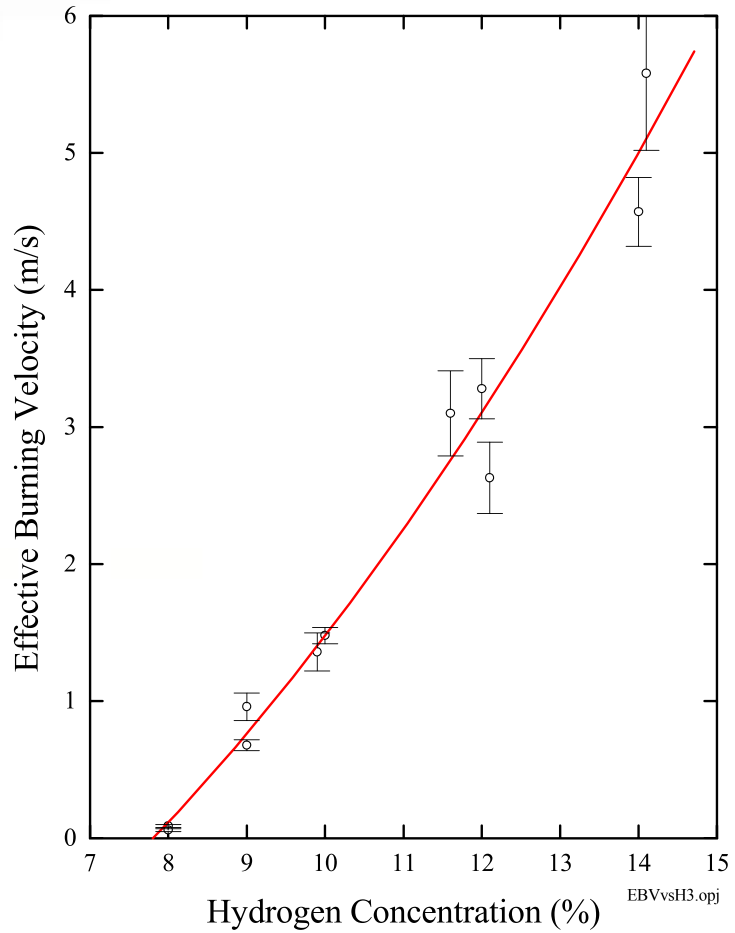


Containment Test Facility

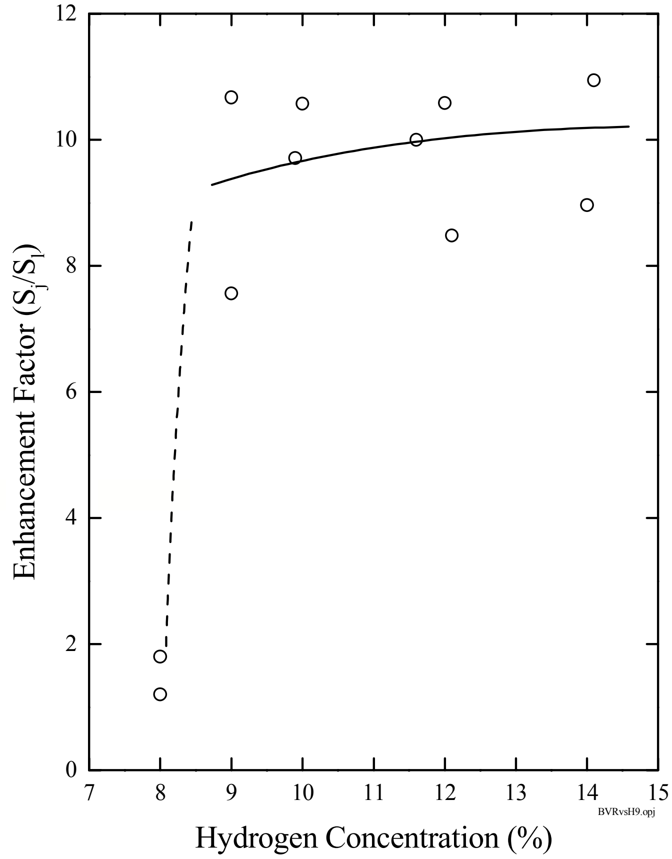
Flame-Jet Ignition Tests



Single-Flame-Jet Ignition Tests



Single-Flame-Jet Ignition Tests (cont.)



Hydrogen Mitigation by Catalytic Recombiner

- **Passive Autocatalytic Recombiner (PAR)**
  - Passive device
  - Self-start at 2% hydrogen at 20C
  - Wet-proofed catalyst
  - Suitable long-term hydrogen management

Continuous Hydrogen Injection

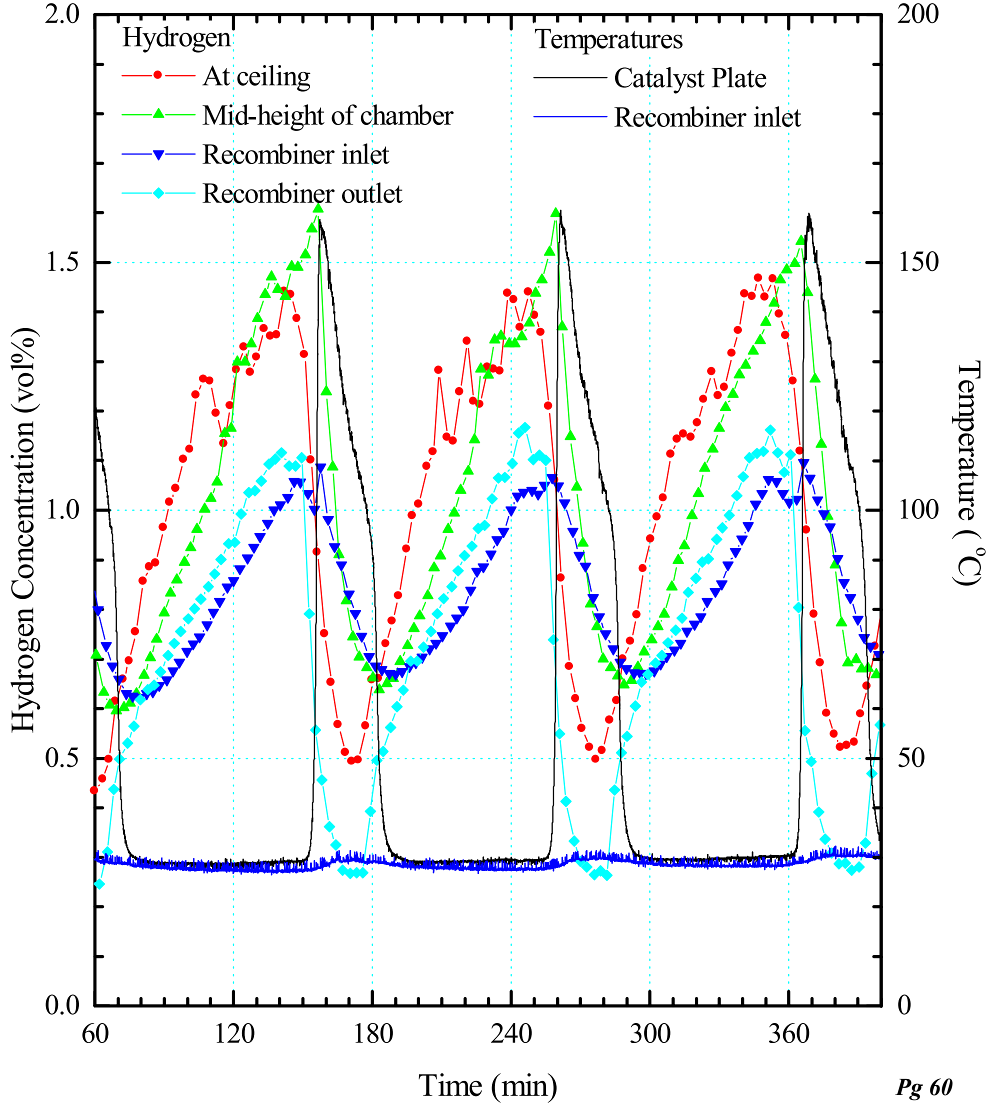
Test conditions:

25°C

100% relative humidity

0.029 kg/h injection rate

Injection at centre bottom of side wall



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